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Radio and Millimeter Observations of the COSMOS Field

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Abstract. The Cosmic Evolution Survey (COSMOS) targets an equatorial two square degree field covering the full electromagnetic spectrum. Here we present first results from observations of the COSMOS field in the millimeter and centimeter regime done with the IRAM 30 m/MAMBO array and NRAO's Very Large Array (VLA) at 250 GHz and 1.4 GHz, respectively.

1. Introduction

The Cosmic Evolution Survey (COSMOS) project (Scoville et al. 2007) is a pan-chromatic imaging and spectroscopic survey of a two square degree field designed to probe galaxy and SMBH (super-massive black hole) evolution as a function of cosmic environment. It is the largest contiguous field ever mapped by *HST*. Numerous state-of-the-art imaging campaigns at all wavelengths (X-ray to cm) are underway for the COSMOS *HST* field.

One major scientific rationale of the COSMOS survey is to study the relation between the large-scale structure (LSS) and the evolution of galaxies and SMBHs. In a ΛCDM cosmology, galaxies in the early universe grow through two major processes: dissipational collapse, and merging of lower-mass protogalactic and galactic components. Their intrinsic evolution is then driven by the conversion of primordial and interstellar gas into stars, with galactic merging and interactions triggering star formation and starbursts. Mergers also can perturb the gravitational potential in the vicinity of the black hole, thus initiating or enhancing AGN activity. Several lines of evidence suggest that galaxy evolution and black hole growth are closely connected; COSMOS offers the chance to observe this connection directly. While there is general agreement over this qualitative picture, the timing/occurrence of these events and their dependence on the local environment remains to be observationally explored (e.g., Ferguson, Dickinson, & Williams 2000). To study LSS it is essential to obtain high spatial resolution data over the entire electromagnetic spectrum covering a significant area on the sky, like $2\,\mathrm{deg}^2$ as in the case of the COSMOS survey. Also, surveys of active galactic nuclei benefit from such a combination of areal coverage and depth.

2. Observations

Unlike most existing deep survey fields, the COSMOS field is equatorial and hence has excellent accessibility from all ground-based facilities (current and future such as [E]VLA and ALMA). In addition, it has extensive multi-wavelength coverage (Scoville et al. 2007). This makes it an ideal field in which to analyze the (faint) radio source population as a function of redshift, environment, galaxy morphology, and other properties. The VLA-COSMOS radio observations were matched to study a range of important issues related to the history of star formation, the growth of super-massive black holes, and the spatial clustering of galaxies. The ongoing spectroscopic surveys within the COSMOS project are also targeting well-defined samples of radio sources as part of the overall program. In addition, the VLA-COSMOS radio survey is providing the absolute astrometric frame for the COSMOS field (Aussel et al. 2007, in preparation), which is important given the field's large size.

Table 1. Radio Surveys at 1.4 GHz.

Field	Area (deg^2)	rms ($\mu\mathrm{Jy\,beam}^{-1}$)	resolution ($'' \times ''$)	# of objects	Reference
COSMOS	2	10.5	1.5×1.4	3643	Schinnerer et al. (2007)
HDFN	0.35	7.5	2.0×1.8	314	Richards (2000)
FIRST	10,000	150	5	1,000,000	Becker et al. (1995)
FLS	5	23	5	3565	Condon et al. (2003)
VIRMOS	2	17	6	1054	Bondi et al. (2003)
ATHDFS	0.35	11	7.1×6.2	466	Huynh et al. (2005)
ATESP	26	79	14×8	2960	Prandoni et al. (2001)
PDS	4.56	12	12×6	2090	Hopkins et al. (2003)
ELAIS[a]	4.22	27	15	867	Ciliegi et al. (1999)
Lockman	0.35	120	15	149	de Ruiter et al. (1997)
NVSS	34,000	350	45	1,700,000	Condon et al. (1998)

[a]Consists of three ELAIS survey fields: N1, N2, and N3.

2.1. Millimeter: MAMBO-COSMOS Survey (COSBO)

The ongoing MAMBO-COSMOS survey has been imaging the COSMOS field at wavelength 1.2 mm (Bertoldi et al. 2007) using the 117-channel Max-Planck Bolometer array (MAMBO-2; Kreysa et al. 1998) at the IRAM 30 m telescope on Pico Veleta, Spain. The effective beam FWHM is 10.7 arcsec, and the undersampled field of view is 4 arcmin. The observations were done in observing pools spread over the winters 2003–2004 and 2004–2005, continuing in winter 2005–2006. Atmospheric conditions were generally good during the observations. The total on-sky integration time was 78 hours. The standard on-the-fly mapping technique was used.

So far an area of about $400\,\mathrm{arcmin}^2$ down to a depth of $1\,\mathrm{mJy\,beam}^{-1}$ has been covered, and at least 15 secure sources have already been detected for detailed follow-up, of which nine (i.e., 60%) are also significantly detected in our 1.4 GHz VLA-COSMOS image (Bertoldi et al. 2007).

2.2. Centimeter: VLA-COSMOS Survey

The VLA-COSMOS survey consists of three different wide-field imaging projects at 1.4 GHz: (1) an initial pilot project (Schinnerer et al. 2004), where the mosaicking strategy for the large project was tested, (2) the large project, which covers the entire COSMOS field down to an rms depth of $\sim 10\,\mu$Jy (Schinnerer et al. 2007), and (3) the ongoing deep project, which uniformly images the central $30'$ of the COSMOS field.

All observations were done using the VLA in its A configuration. For the large project, observations in the C array provided information on shorter baselines. A total of 275 hr were spent to observe the 23 pointings of the final mosaic of the large project. The resulting resolution of $1.5'' \times 1.4''$ (FWHM) is very well-matched to the other COSMOS datasets. A total of over 3,600 sources above 4.5σ have been detected.

The combination of high sensitivity and high spatial resolution over a large area in the VLA-COSMOS large project (see Table 1) bridges the gap between shallow, wider-field surveys such as FIRST (Becker, White, & Helfand 1995) and NVSS (Condon et al. 1998) with about one million sources, and ultra-sensitive ($\leq 3\mu$Jy), narrow-field (single VLA primary beam $\sim 30'$ FWHM) studies of a few hundred sources, such as those by Owen, Fomalont, and others.

3. Results

The MAMBO map of the central COSMOS field is shown in Figure 1 (Bertoldi et al. 2007). Fifteen sources are detected at significance between 4 and 7σ, eleven of which are also detected at 1.4 GHz with the VLA with a flux density $> 30\,\mu$Jy (3σ). The 250 GHz source surface density in the COSMOS field is comparable to those seen in other deep mm fields. The multi-frequency properties of the MAMBO sources, including: (i) *HST*/ACS i-band magnitudes (or limits) and morphologies, (ii) ground-based optical and near-IR magnitudes, (iii) *XMM* X-ray flux densities, and (iv) VLA radio flux densities suggest that most of these sources are similar to sources detected in other surveys. Some relatively bright MAMBO sources do not show obvious radio counterparts to very faint levels; these sources could be dusty starburst galaxies at redshifts > 3.5.

Radio components above 4.5σ were extracted from a two square degree area in the VLA-COSMOS 1.4 GHz image indicated in Figure 2 using a parametric fitting routine. Visual inspection was used to combine multiple components into single sources if these were fitted by more than one component. Eighty such sources are present in the catalog, and most of them are radio galaxies showing prominent radio lobes. The final catalog consists of 3,643 sources and is presented in Schinnerer et al. (2007). The final image and catalog are publicly available via the COSMOS archive at IRSA/IPAC.

Besides the aim of studying the faint radio population, the VLA-COSMOS large project, in conjunction with the overall COSMOS datasets, also enables the study of interesting single targets such as wide-angle tail (WAT) radio galaxies. One such WAT and its environment are studied in detail in Smolčić et al. (2007),

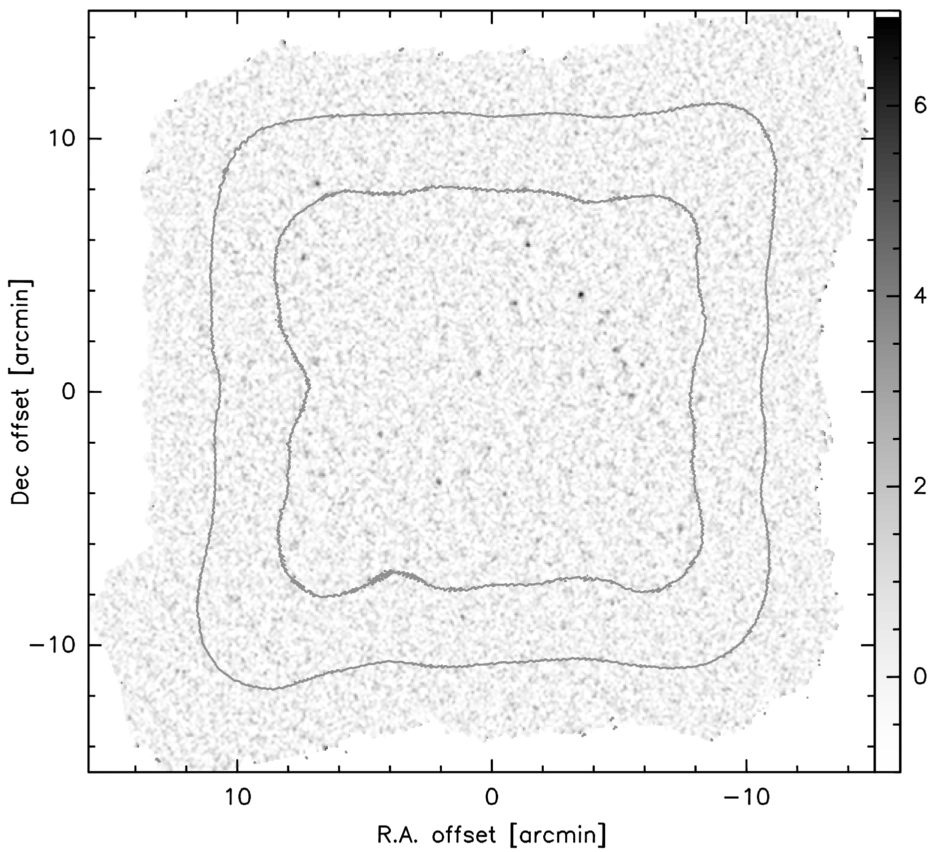

Figure 1. MAMBO 250 GHz signal-to-noise map smoothed to 12″ resolution from the original 10.7″. The rms noise level is < 1 mJy per 10.7″ beam in the inner contour (ca. 250 arcmin^2), and < 2 mJy within the outer contour (ca. 450 arcmin^2).

where the authors find evidence for ongoing merging of galaxy clusters. Figure 3 shows this radio galaxy CWAT-01.

The optical counterparts of radio sources are targeted in the ongoing spectroscopic surveys of the COSMOS field, which use the ESO VLT/VIMOS spectrograph (Lilly et al. 2007) and the Magellan/IMACS spectrograph (Impey et al. 2007; Trump et al. 2007). After these surveys are finished, it is expected that over 1,500 spectra will exist for faint radio sources.

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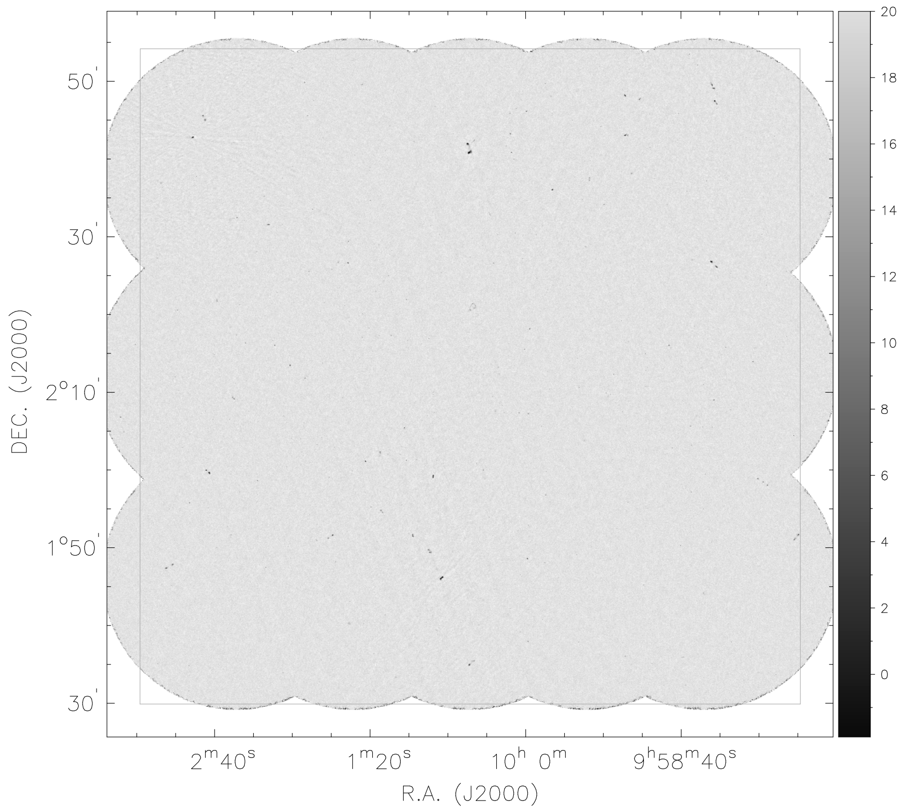

Figure 2. Map of the S/N of the VLA-COSMOS large project as constructed using an SExtractor sensitivity map. Lighter shades indicate lower S/N values. The grey box shows the area in which radio sources were identified.

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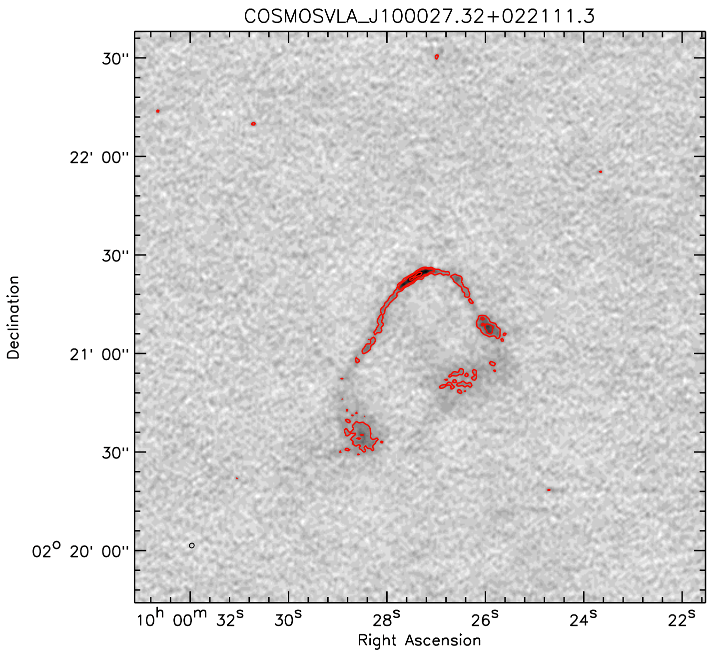

Figure 3. This WAT radio galaxy is located in a galaxy cluster that is part of an assembly of five clusters discussed in detail by Smolčić et al. (2007). The bent shape of the radio jets indicates that the WAT host galaxy is moving through the intra-cluster medium. Together with the orientations of the other clusters, this suggests that we are witnessing the build-up of a larger galaxy cluster with a mass of roughly 20% that of the Coma cluster.

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Discussion

Yun: It is striking that the brightest millimeter source in the COSMOS field is not detected in radio, as is the case in the HDF and GOODS-N field. Is there any peculiarity to the millimeter source, such as a spatial extension? Also, the fraction of sources detected in radio, 2/9, is small for the 3.5σ sources. Is this a problem with low S/N in the radio and/or mm data?

Schinnerer: The brightest MAMBO source is fairly close to being unresolved, so nothing is special about the structure of this source. The low detection rate for millimeter sources between 3.5 and 4.0σ is likely a combination of the radio data's not being sensitive enough to detect the weak millimeter sources and maybe spurious detections with MAMBO.

Scoville: Your COSMOS VLA survey should not be perceived as shallow since it is really comparable in depth ($10\,\mu$Jy) to the Richards survey of the HDF ($7\,\mu$Jy).

Schinnerer: At its depth and angular resolution the VLA-COSMOS survey is quite unique, probing actively star-forming galaxies out to redshifts of 1.5–2. It was not designed to search for counterparts to high-z SMGs. However, the upcoming deep extension of the central $30'$ will improve the situation.

Aretxaga: Could you please elaborate on which bands have been used for the optical *photometric* redshifts of the SMGs in COSMOS, and how extinction of perhaps several magnitudes has been incorporated into the interpretation?

Schinnerer: For the presented photo-zs, ground-based $UBVgriK$ bands have been used. The effect of large extinction would be to make the optical SED redder, which is then closer to the early-type template. No specific attempts have been made to account for large extinction. With the new IRAC data, the photo-zs should improve quite a bit.

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